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A multi-objective local search heuristic for scheduling Earth observations taken by an agile satellite

Panwadee Tangpattanakul[a], Nicolas Jozefowiez[b,c,*], Pierre Lopez[b,d]

[a] Geo-Informatics and Space Technology Development Agency (GISTDA), 120 The Government Complex, Chaeng Wattana Road, Lak Si, Bangkok 10210, Thailand
[b] CNRS, LAAS, 7 avenue du Colonel Roche, F-31400 Toulouse, France
[c] Univ de Toulouse, INSA, LAAS, F-31400 Toulouse, France
[d] Univ de Toulouse, LAAS, F-31400 Toulouse, France

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ABSTRACT

This paper presents an indicator-based multi-objective local search (IBMOLS) to solve a multi-objective optimization problem. The problem concerns the selection and scheduling of observations for an agile Earth observing satellite. The mission of an Earth observing satellite is to obtain photographs of the Earth surface to satisfy user requirements. Requests from several users have to be managed before transmitting an order, which is a sequence of selected acquisitions, to the satellite. The obtained sequence has to optimize two objectives under operation constraints. The objectives are to maximize the total profit of the selected acquisitions and simultaneously to ensure the fairness of resource sharing by minimizing the maximum profit difference between users. Experiments are conducted on realistic instances. Hypervolumes of the approximate Pareto fronts are computed and the results from IBMOLS are compared with the results from the biased random-key genetic algorithm (BRKGA).

1. Introduction and background

This paper addresses a multi-objective optimization problem associated with selecting and scheduling observations of an agile Earth observing satellite. We consider the case where multiple users order requests to the satellite. A local search is proposed to solve the problem and experiments are conducted on realistic instances.

The mission of Earth observing satellites (EOSs) is to obtain photographs of the Earth surface, in order to satisfy the requirements from users. EOSs can acquire photographs, while moving along their orbits. They spend a period of several days to perform a cycle of orbit. The whole area of the Earth is viewed, when the satellites complete a full cycle (Habet, Vasquez, & Vimont, 2010). EOSs carry different instruments depending on their usages, e.g. optical camera or infrared camera. Most of them operate at low altitudes. Hence, when they move over the visible areas of the required photographs, the photographs can be captured as in Fig. 1. Then, the satellites will try to transfer the data of the acquired images directly to the ground station center after acquiring them, if possible. Otherwise, the data are stored in the on-board limited memory until the satellites are in the possible transferring range to the ground station center.

Among the various types of EOSs, only so-called “agile” satellites are considered in this paper. An agile EOS is equipped with only one fixed on-board camera, but the satellite uses an attitude and orbit control system (AOCS) to be able to turn around three axes: roll, pitch, and yaw (Lemaître, Verfaillie, & Jouhaud, 2000). An example of an agile satellite is PLEIADES, which was developed by the CNES, the French Space Agency. The starting time for taking each image of this satellite is not fixed, but it must be in a given time interval, which is called a time window. Therefore, an agile satellite has an important advantage when compared to a non-agile satellite. On the one hand, this gives agile satellite better efficiency of the whole system. On the other hand, the problem of selecting and scheduling the candidate images is more difficult to solve, since the search space under consideration is larger (Lemaître, Verfaillie, Jouhaud, Lachiver, & Bataille, 2002b).

In this work, the satellite management process is considered when several users order requests to a ground station center. The requests cannot be assigned directly to a satellite; the ground station center has to select and schedule the candidate images, according to some limitations of the satellite, before the obtained sequence is transmitted.

For solving the Earth observation scheduling problem, there are several studies on agile EOSs. For example, a combination of genetic algorithm and simulated annealing was proposed to solve this

* Corresponding author at: LAAS-CNRS, 7 avenue du Colonel Roche, F-31400 Toulouse, France. Tel.: +33 5 61 33 69 08.
E-mail address: nicolas.jozefowiez@laas.fr (N. Jozefowiez).

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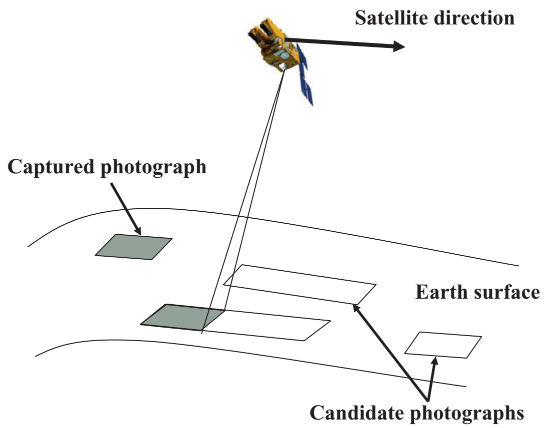

Fig. 1. The satellite captures the photographs (Mansour & Dessouky, 2010).

problem in Li, Xu, and Wang (2007). The performance of the proposed algorithm was compared with the simulated annealing alone. In Lemaître et al. (2002b), four methods consisting of a greedy algorithm, a dynamic programming procedure, a constraint programming model, and a local search method were applied in order to solve a simplified version of the scheduling problem for agile EOSs.

The ROADEF 2003 challenge was about the management problem of an agile EOS mission (see http://challenge.roadef.org/2003/en/). The challenge aims at finding a feasible schedule that maximizes the total profit, computed from the sum of request gains, which are associated with the complete or partial acquisition of each request. All the data description and optimization criterion are explained in Verfaillie, Lemaître, Bataille, and Lachiver (2002). Note that the problem considered in this challenge was a simplified version of the real Earth observation satellite management problem; for example, neither data download nor energy and thermal limitations are taken into account.

The winner of this challenge used an algorithm based on simulated annealing for solving the scheduling problem (Kuipers, 2003). The second prize winner proposed an algorithm based on tabu search (Cordeau & Laporte, 2005). The authors adapted the unified tabu search algorithm (Cordeau, Laporte, & Mercier, 2001), which was developed for the vehicle routing problem with time windows. Moreover, a tabu search algorithm hybridized with a systematic search was applied to solve this problem in Habet et al. (2010). All these works considered the scheduling problem for an agile EOS as a mono-objective optimization problem (total profit maximization).

Our work considers the acquisition scheduling problem of an agile EOS, where the requests emanate from several different users. We need to optimize two objective functions, which are to maximize a total profit and simultaneously ensure the fairness of resource sharing for all users. Thus, this problem is modeled as a multi-objective optimization problem. The second objective, which is added in order to ensure the fairness, amounts to minimize the maximum profit difference between users. Some researchers studied multi-objective optimization problems for space applications (Arias-Montaño, Coello, & Mezura-Montes, 2012; Gabrel & Vanderpooten, 2002; Wang, Jing, Li, & Chen, 2007). Furthermore, some literature considered as an objective the fairness among users (Lemaître et al., 2002a). Multiple end-users of agile EOSs were considered and sharing principles were adopted to select the subset of candidates based on utility levels. In Bataille, Lemaître, and Verfaillie (1999) and Lemaître, Verfaillie, and Bataille (1999), the use of two objective functions related to fairness and efficiency was proposed. Three ways were discussed for solving this sharing problem: the first one gives priority to fairness, the second one to efficiency, and the third one computes a set of trade-offs to help a human to make decisions. For the multicriteria methods,

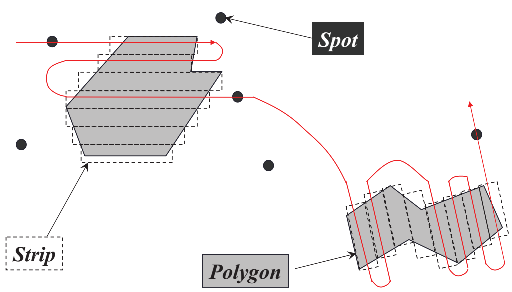

Fig. 2. Example of both request's shapes and order for taking the strips after management (Lemaître et al., 2002b).

instead of building a complete set of nondominated solutions, the authors only searched for a decision close to the line with a specified slope on the objective function plane. In Bianchessi, Cordeau, Desrosiers, Laporte, and Raymond (2007), the selecting and scheduling requests for the multi-satellite, multi-orbit, and multi-user were studied, and tabu search was used to solve the problem. The fairness was taken into account, but it was not considered as an objective function. The authors borrowed an ordered weighted average from Yager (1988) to ensure the fairness of the solutions. The experiments test these algorithms with the data instances provided by the CNES.

This paper proposes an indicator-based multi-objective local search, which is a multi-objective metaheuristic algorithm, for selecting and scheduling the subset of candidate photographs. Section 2 presents the description of the multi-user Earth observation scheduling problem. Then, the indicator-based multi-objective local search is explained in Section 3. Section 4 presents the computational results. This section compares the results from the indicator-based multi-objective local search and from the biased random-key genetic algorithm. Finally, conclusions and perspectives are discussed in Section 5.

2. Problem description

2.1. Informal presentation

The instances, which are modified from the ROADEF 2003 challenge instances, will be described in detail. They will be used in the experiments, for testing the performance of the proposed algorithm in our work.

Each request can be of two types: mono or stereo. Each area is taken only once for mono requests, whereas for stereo requests, each area must be acquired twice in the same direction but from different angles. Two possible shapes of request, which are a spot or a polygon, can be required. The spot is a small circular area with a radius of less than 10 km. The polygon is a polygonal area ranging from 20 to 100 km. Both shapes have to be managed by transforming the requests into several rectangular shapes called strips. Each polygon is decomposed into several strips of the same width but with variable lengths. A spot is considered as a single strip. Each strip can be taken once at a time by the camera on the satellite. An example of request shapes and order for taking the strips after management is illustrated in Fig. 2. There are two possible directions to acquire each strip. Both directions are parallel to the length of the strip, but in the opposite directions as shown in Fig. 3. Among two of them, only one acquired direction can be selected. The strip, associated with one possible acquired direction, is called an acquisition. Thus, each strip consists of two possible acquisitions. The interval of possible starting times for taking each acquisition can be computed, depending on the acquired direction, from the earliest and latest visible time of the two extremities of the strip, and the acquired duration time of the strip.

Each acquisition generates a profit. Thus, for the observation scheduling problem, the objective is total profit maximization.